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GUIDELINES FOR SAFE LOCAL POST-WELD HEAT TREATMENT OF PIPE NOZZLE REPAIR WELDS IN HEAVY WATER PLANT VESSELS

Report No 87-269-K

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ABSTRACT

The report describes the results of finite element analyses of thermal stresses induced during localized post-weld heat treatment (PWHT) of welds on pipes entering pressure vessels. This situation is of practical concern because of the frequent need to repair piping nozzle connections on heavy water plant vessels. For practical and economic reasons, it is often desirable to confine PWHT to the immediate neighbourhood of the weld. However, in any case of a local PWHT, it is very important to limit the stresses due to thermal gradients. Two important limiting factors were found. In all cases, it was found that temperatures at the surface of the vessel should be maintained below 170^{o}C (340^{o}F) to avoid overstressing the vessel. If higher temperatures are inevitable, a full heating band around the circumference of the vessel is required. For large diameter pipes (100 mm and above) it is also important to limit the thermal gradient down the length of the pipe.

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EXECUTIVE SUMMARY

This report describes the results of a numerical (finite element) study of the stresses induced during local post-weld heat treatment (PWHT) of weld on a piping nozzle entering a large pressure vessel. This situation is of practical concern because of the frequent need to repair piping nozzle connections on heavy water plant vessels. There are practical and economic advantages to carrying out the PWHT on a confined area near the weld repair. However, it is essential to ensure that thermal stresses developed during such a PWHT do not leave behind unacceptable residual stresses. This study examined several typical pipe nozzle configurations to find out when it would be possible to heat treat the nozzle/pipe area locally and when it would be necessary to enlarge the heat-treated zone to include a larger portion of the vessel.

The study found that for small diameter pipes, the most important limitation on carrying out local PWHT is the maximum temperature on the outer surface of the vessel. If this exceeds 170°C (340°F), thermal stresses can exceed yield and a more widely applied heat treatment should be used (this would generally include a circumferential band around the whole vessel). For larger diameter pipes, it is also necessary to limit the thermal gradient along the length of the pipe.

The study was initiated and sponsored by the Chemistry and Metallurgy Department of Central Nuclear Services.

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To: Mr. B. Montford
Manager, Chemistry and Metallurgy Dept
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GUIDELINES FOR SAFE LOCAL POST WELD HEAT TREATMENT OF PIPE NOZZLE REPAIR WELDS IN HEAVY WATER PLANT VESSELS

1.0 INTRODUCTION

The Chemistry and Metallurgy Department (Central Nuclear Services) have supported an evaluation of practical concerns related to the heat treatment of nozzle welds on pressure vessels. Specifically, welds on vessels used in hydrogen sulphide service require post-weld heat treatment (PWHT) to relieve stresses and reduce problems associated with stress corrosion cracking. Repair welds are typically very localized and it is economically desirable to limit the heat treatment to a region immediately around the weld. However, localized PWHT can itself create high residual stresses if it is not properly designed and controlled.

Heat treatment requirements for repair welds on the body of a vessel or on piping systems are well defined. Where a repair weld is on the body of a vessel, PWHT would normally involve heating a continuous band around the circumference of the vessel. If the weld is on a section of pipe remote from any connections, the heated band would be around the pipe itself. Heat treatment of nozzles, however, is less straightforward since the proximity of the weld to the pressure vessel body may lead to high thermal stresses during PWHT. This report examines several examples of this type of geometry and contains specific recommendations on the minimum distance between the heated band on a branch pipe and the main body of the pressure vessel. The recommendations are based on finite element simulations of PWHT processes.

This report is about specific options for local PWHT. It is not a comprehensive description of the requirements for PWHT.

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2.0 BACKGROUND

The requirements for heat treatment of fabrication and repair welds in nuclear grade pressure vessels are specified in the ASME Boiler and Pressure Vessel Code/1/. The relevant paragraph is quoted in Appendix A of this report.

Post-weld heat treatment of carbon steels involves temperatures around 600° C (1150° F). At these temperatures, the yield strength of the material is substantially reduced so that residual stresses locked in by welding will be largely eliminated through relaxation and creep. However, when a large vessel is heated non-uniformly, there will be differential expansion and the danger of high thermal stresses. If this occurs, significant residual stresses may be left behind when the vessel cools. In effect, poorly executed local PWHT will re-distribute residual stresses but not eliminate them.

For vessels with simple cylindrical shells, the normal strategy for controlling thermal stresses is to uniformly heat a circumferential band around the vessel. This approach is generally safe, provided that:

- The vessel is properly supported so that there is no danger of collapse or distortion while the material is in a softened state;
- The vessel is free to expand axially so that stresses in the vessel wall and in attached piping are minimized;
- The thermal gradients on either side of the heated band are gradual enough to avoid high stresses in the wall of the vessel.
- Temperatures are increased and decreased slowly enough to keep thermal gradients through the wall of the vessel acceptably low.
- Internal components of the vessel are free to move separately from the outer shell so that they are not damaged when the outer shell expands.

Geometries that are more complicated that simple cylinders will normally require more elaborate heating arrangements covering larger areas of the vessel./2/

3.0 THERMAL STRESSES IN PIPE/VESSEL INTERSECTIONS

A common repair situation involves relatively small diameter piping that joins a larger vessel through a nozzle or other penetration. (See Figure 1.) If the repair involves welding on or immediately adjacent to the vessel, the best approach would be to evenly heat a band around the circumference of the vessel to the temperature time-history required for the type, grade and thickness of steel involved. Similarly, if the weld is on a section of pipe remote from any connections, the heated band would be around the pipe. Between these extremes is the very common case of a weld on a section of pipe near a nozzle. When can a local PWHT be safely confined to the pipe and when would it be necessary to include a band around the whole vessel?

3.1 Analysis Method

This report considers several piping nozzle geometries that occur commonly at the Bruce heavy water plant. The temperature distributions and stresses resulting from various local PWHT approaches were analyzed and, based on these analyses, recommendations are made as to what types of local PWHT can be safely used. The geometries were:

- A one-inch Schedule 80 pipe entering a one-inch thick shell;
- A two-inch Schedule 160 pipe entering a 3/8 inch thick shell; and
- A six-inch Schedule 80 pipe entering a three-inch thick shell.

The analysis was based on finite elements models of these pipe/shell intersections. In each case, temperature distributions due to local application of the PWHT were estimated and thermal stresses calculated. The simulations were repeated for different separation distances between the heated band on the pipe and the outer surface of the vessel. This established the relationship between the location of the PWHT band and the resulting thermal stresses.

Details of the analysis are contained in Appendix B. Methods used in this study were first developed as part of a general study of thermal stresses arising from PWHT conducted by the Mechanical Research Department for Bruce NGS 'A', under the auspices of the Chemistry and Metallurgy Department of CNS /2/.

3.2 Summary of Results

Our analysis show that there are two main limitations on how close a PWHT band on a branch pipe can be brought to the main vessel before it is necessary to include a circumferential band around the whole vessel. These are:

Temperature at the Shell Surface

Heat from the PWHT band on the pipe will flow into the vessel, creating a "warm spot" on the vessel wall and a zone of thermal stress at the inside corner of the penetration. Our analysis shows that so long as the temperature on the outer surface of the vessel remains below about 170° C (340° F), stresses in the vessel will be below yield and there will be no residual stresses when the heat treatment is completed. (See Figure 3 for a plot of peak stress versus maximum temperature on the vessel wall.)

The temperature of the "warm spot" on the vessel will depend on the distance between the heated band on the pipe and the surface of the vessel and on the component thicknesses. Obviously, when the heated band is located close to the vessel wall, the temperature in the "warm spot" will be relatively high. However, the minimum distance corresponding to a surface temperature of 170°C also depends on the relative thickness of the pipe and vessel wall. Heat from the PWHT band flows down the pipe into the vessel. The wall of the vessel acts as a heat sink and the thicker the wall, the slower the rate of temperature rise. As well, the capacity of the pipe to deliver heat to the vessel wall will vary with its thickness and diameter. From our calculations, we found that with a relatively thin pipe joining a thick shell (1 in. Sch 80 pipe into a 1 in. thick shell) the minimum separation distance between the inner edge of the PWHT band and the shell surface could be as little as 50 mm. However, for the thicker 2 in. Sch 160 pipe joining a 3/8 in shell, a 100 mm minimum separation was necessary to avoid overheating and over stressing the shell.

Temperature Gradient in Pipe

A very sharp temperature gradient at the edge of the heated band will create excessive stresses in the pipe. The temperature gradient in the pipe depends almost exclusively on the distance between the heated band and the vessel wall since the end-point temperatures are constrained by other requirements (the temperature at the edge of the band must be at least 600° C to meet the requirements for PWHT, while the temperature at the vessel wall should not exceed 170° C, as explained above.) In our analysis, we found that the stresses in the pipe remained below yield if the distance between the inner edge of the headed

band and the vessel wall was at least $4\sqrt{Rt}$ (where R is the pipe outer radius and t is the pipe wall thickness). In practical terms, this condition is significant only for relatively large diameter pipes (such as the 6 in. pipe considered in this study). For small pipes, the distance will be limited by the vessel surface temperature criterion mentioned above.

(The British Standard BS5500 recommends that for circumferential band type local PWHT, a temperature of at least half of the maximum in the band be maintained for a distance of $2.5\sqrt{Rt}$ beyond the edge of the band/3/. This criterion is consistent with the results of our calculations.)

4.0 CONCLUSIONS AND RECOMMENDATIONS

The study reported here was limited in scope to several "typical" pipe/vessel intersection geometries and it would be imprudent to generalize the findings too widely. However, the results of the analyses were consistent and do lead to some useful conclusions.

The relationship between temperature on the outer surface of the vessel next to the pipe and the stress at the inner corner of the penetration (the most highly stressed region in most instances) is not exact. However, stresses were invariably above yield when the surface temperature exceeded 200° C and was below yield when the temperature was less than 170° C. We recommend therefore that if the PWHT band on the branch pipe is sufficiently close to the vessel that the surface temperature on the vessel is likely to exceed 170° C, the heat treatment should include a band around the body of the vessel. (This will cause a general expansion of a circumferential band of the vessel and eliminate the local high stresses due to the "hot spot".

The temperature on the vessel outer surface depends in various ways on the geometry of the pipe/vessel intersection, but the most important parameter by far is the distance between the heated band and the vessel. To determine the minimum distance between the weld and the vessel, it is necessary to consider both the width of the heated band and the minimum separation distance between the inner edge of the band and the vessel. According to Section NB-4624.3 of the ASME code, the band on the pipe should extend at least 51 mm to either side of the weld (see Appendix A). Temperatures should be maintained close to the PWHT range over the width of this band. An additional allowance of between 50 and 100 mm should be left to ensure that the temperature in the "warm spot" stays below 170° C. According to our analysis, a separation distance of 150 mm between the weld and the surface of the vessel should be safe for all 2 in. or smaller pipes. A distance of as little as 100 mm would be adequate for the combination of small pipes (1 in. Sch 80) and relatively thick vessel walls (1 in or above).

The separation distance between the inner edge of the heated band and the surface of the vessel should also be at least $4\sqrt{Rt}$, where R is the pipe outer radius and t is the pipe wall thickness. Here again, at least 51 mm should be allowed between the centre line of the weld and the edge of the heated band. The $4\sqrt{Rt}$ criterion will limit the minimum separation distance for relatively large pipes, while the warm-spot criterion will be limiting for smaller pipes and tubes.

These recommendations are based on analysis alone. This analysis was based on reliable material data and should be accurate. However, we recommend experimental verification of the relationship between the location of a heated band and the temperature in the "warm spot" for typical pipe/vessel geometries. This would help to make the criteria proposed here more reliable (and hence more useful) for practical maintenance work.

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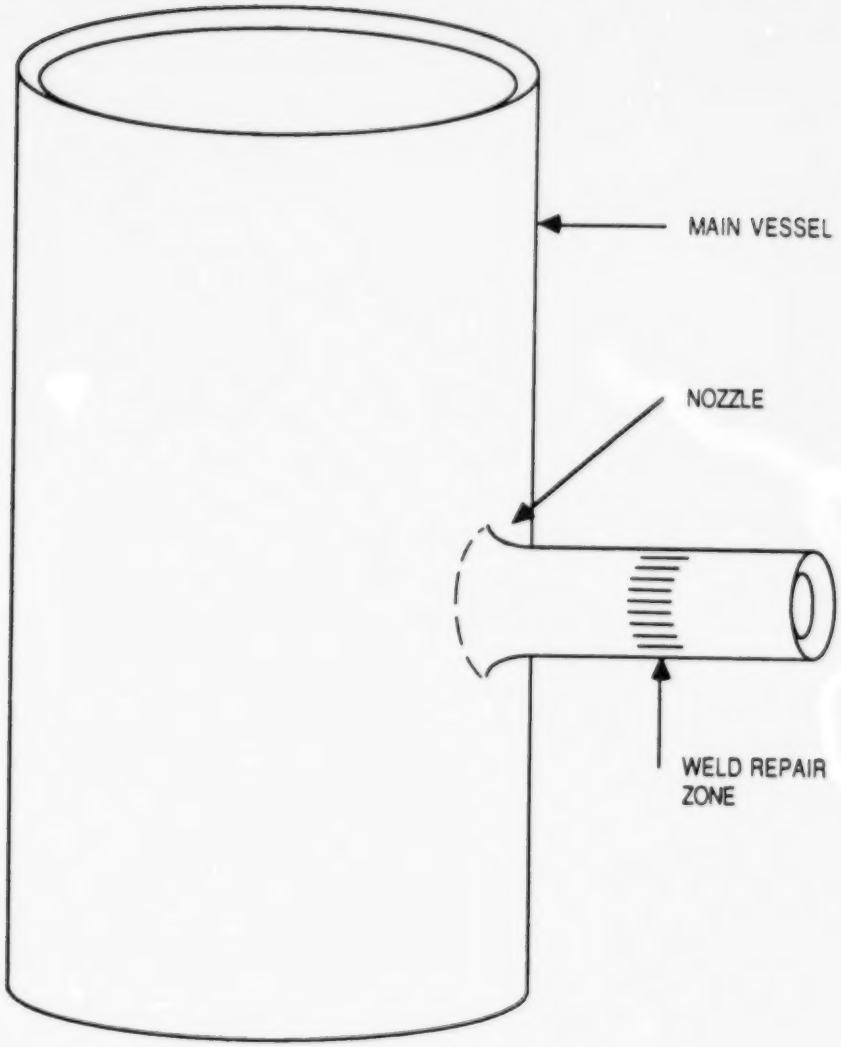

FIGURE 1

GENERAL CONFIGURATION FOR NOZZLE REPAIRS

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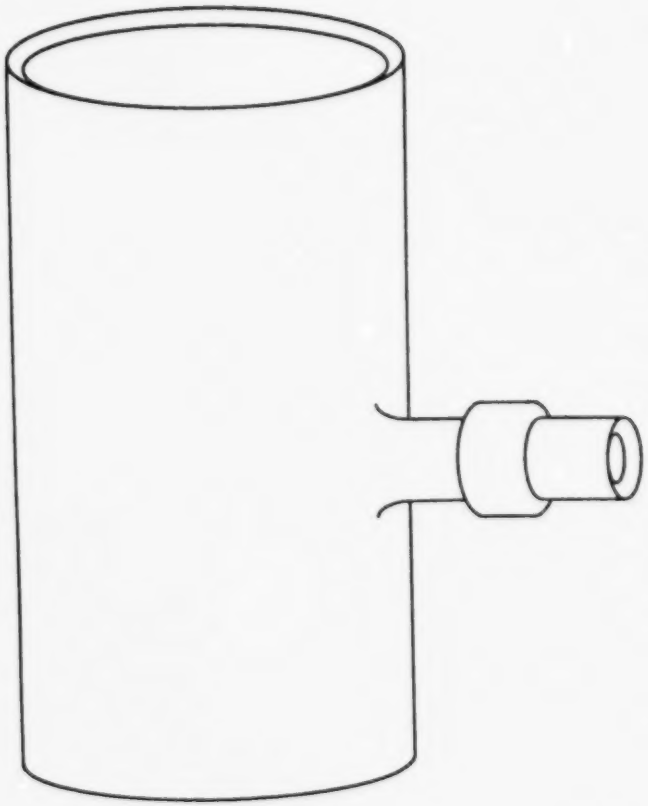

FIGURE 2a

LOCAL HEAT TREATMENT ON BRANCH PIPE ONLY

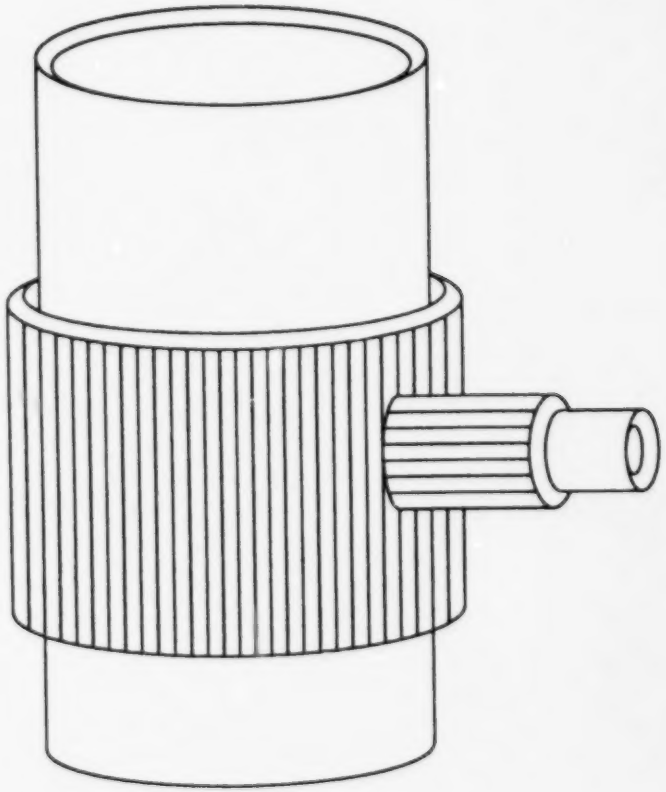

FIGURE 2b

HEAT TREATMENT ON VESSEL (CIRCUMFERENTIAL BAND) AND BRANCH PIPE

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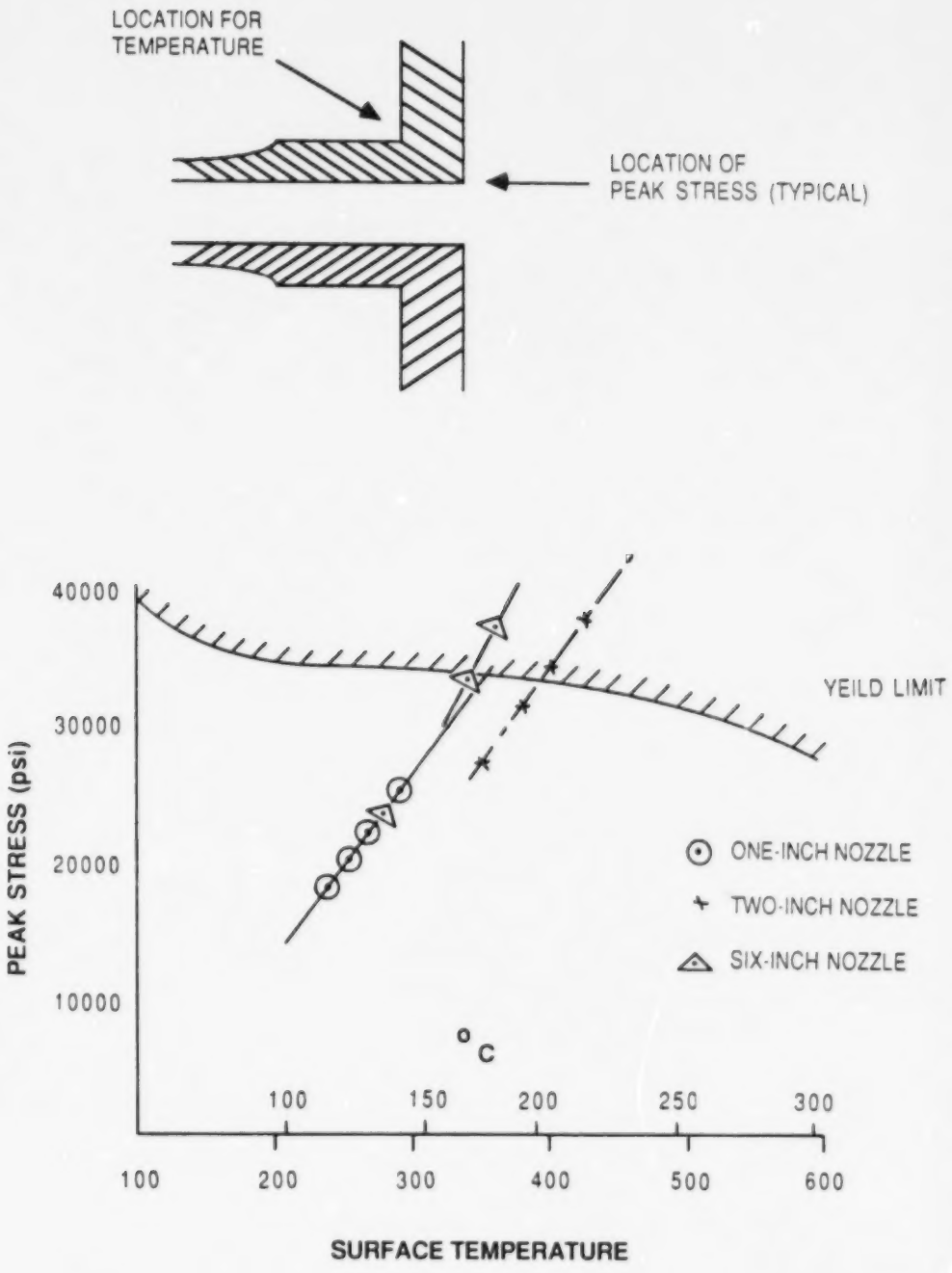

FIGURE 3

RELATIONSHIP OF PEAK STRESS TO MAXIMUM SURFACE TEMPERATURE ON VESSEL

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175727

APPENDIX A

The requirements for heat treatment of fabrication and repair welds in nuclear grade pressure vessels are specified in the ASME Boiler and Pressure Vessel Code, Section III, Division 1, Subarticle NB-4600. Requirements for local PWHT are given in Paragraph NB-4624.3:

> "Welds may be locally post-weld heat treated when it is not practical to heat treat the entire component or item. Local post-weld heat treatment shall consist of heating a circumferential band around the component or item at temperature ranges specified in this Subarticle. The minimum width of the controlled band at each side of the weld, on the face of the greatest weld width, shall be the thickness of the weld or 2 in. (51 mm), whichever is less. The temperature of the component or item from the edge of the controlled band shall be gradually diminished so as to avoid harmful thermal gradients. This procedure may also be used for post-weld heat treatment after repairs."

Heating rates and time-at-temperature are discussed in Subarticle NB-4622.

APPENDIX B

FINITE ELEMENT ANALYSIS OF PIPE/VESSEL CONNECTIONS

The analysis of the three pipe/vessel connections was based on the ABAQUS finite element program*. For model generation and results display, the PATRAN II pre/post processor system was used**.

B.1 ANALYTIC APPROACH

The analysis backing up the recommendations was based on numerical (finite element) simulations of the post-weld heat treatment cycles applied to three "typical" nozzle configurations, viz:

- A one-inch Schedule 80 pipe entering a one-inch thick shell;
- A two inch Schedule 160 pipe entering a 3/8 inch thick shell; and
- A six inch Schedule 80 pipe entering a three-inch thick shell.

For each configuration, the procedure for simulating the PWHT cycle was the same:

- A finite element model was developed for the region of the vessel near the nozzle. These models included a length of pipe attached to the nozzle.
- A thermal transient analysis was carried out, simulating the PWHT cycle. The heat treatment was modeled as a controlled heat flux into an area of the model that represented the section of pipe under the heater elements. Heat was allowed to escape through areas (such as the vessel interior) which would not normally be insulated. The surface temperature of the heated zone were controlled to follow the temperature-time relationship recommended in the ASME pressure vessel code. The result of this analysis was a time-dependent temperature distribution throughout the nozzle/vessel area.

* ABAQUS is a product of Hibbitt, Karlsson and Sorenson Inc. Version 4-5 was used for this analysis

** PATRAN II is a product of PDA Engineering Inc. Release 2.0A was used for this analysis

- Stress analyses were carried out to estimate the thermal stresses due to the heating cycle. These analyses considered incremental changes in stress and material non-linearity. They were able to simulate the growth in stresses during the heat-up period, stress re-distribution during the hold period and finally to estimate the residual stresses left when the cool-down is complete.

For each configuration, this analysis procedure was repeated several times with different separation distances between the heated band and the vessel surface.

B.2 SAMPLE RESULTS

Figures B-1 to B-4 show sample results from the analysis of the two-inch Schedule 160 Nozzle joining a 3/8 inch thick vessel wall. Figure B-1 shows the finite element grid for a region of the model near the nozzle. This model assumes an axis of symmetry that lies along the centre line of the nozzle and pipe.

Figure B-2 shows the temperature distribution in the nozzle after the warm-up stage of the PWHT. The heated band extended from 2.2 inches below the shell surface to 4.8 inches below. Temperatures are represented with different colours. The hottest area (under the heater band) is shown in red, while the cooler regions are shown in light blue. For this particular analysis, the temperature at the intersection of the nozzle and the vessel is approximately 450^{o} F.

Figures B-3 and B-4 show stress distributions. Here, colours represent levels of the Mises stress invariant (which is an indication of whether or not yield will occur. Figure B-3 shows the stress distribution at the end of the warm-up period. The highest stresses occur on the inner surface of the shell, at the inner corner of the nozzle. The peak stress here exceeds the elastic limit of the material at 450^{o} F so that yielding will occur. The consequence of this local plastic deformation is shown in Figure B-4. This is a plot of the residual stresses left behind after the PWHT is complete. There is a very small area of yield-level stresses left in the inner corner region. These stresses will have a significant tensile component in the circumferential direction, and will be prone to stress-related corrosion and even stress-corrosion cracking. It is because of this over-stress condition that we recommend keeping the temperatures at the the vessel surface below 350^{o} F.

Figure B-5 shows the stress distribution on the inner surface of a six-inch diameter nozzle entering a three-inch thick shell. Here there are two areas of high thermal stresses - a zone on the inner corner of the nozzle/vessel intersection, and a second large zone on the inner surface of the nozzle (or pipe) This second zone is a result of the bending moments generated in the

pipe when the heated region attempts to expand radially, but is confined by the thick shell wall.

This analysis was based on a more elaborate three-dimensional model of the nozzle geometry. This approach was selected in this case because the larger nozzle is not so accurately modeled with an axisymmetric finite element mesh.

REFERENCES

1. ASME Boiler and Pressure Vessel Code. Section III. "Nuclear Power Plant Components". Revised 1983.

2. J.D. Tulk, "Weld Repair in Nuclear Pressure Vessels." Ontario Hydro Research Division Report 82-217-K, July 5, 1982.

3. British Standard 5500. "Unfired Fusion Welded Pressure Vessels", Revised, April 1980.

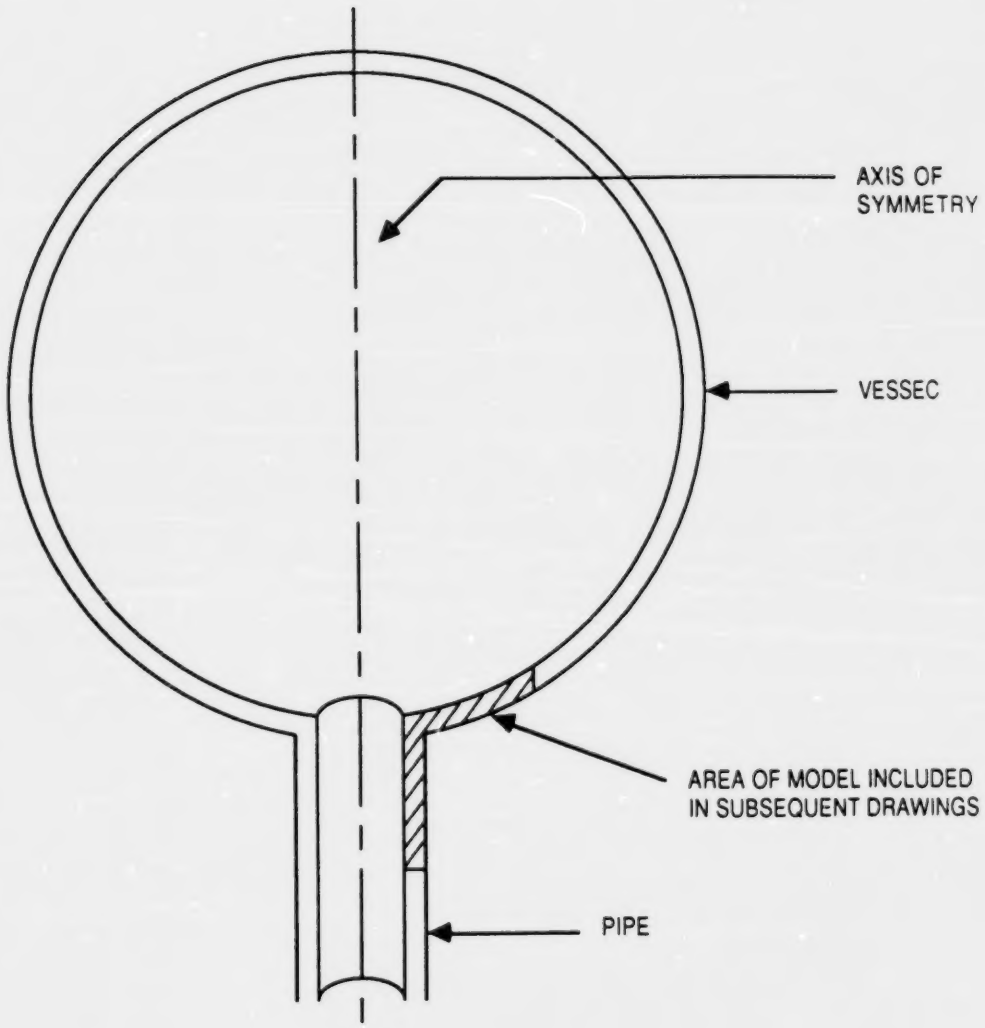

FIGURE B.1

SCHEMATIC VIEW OF TWO-INCH NOZZLE MODEL

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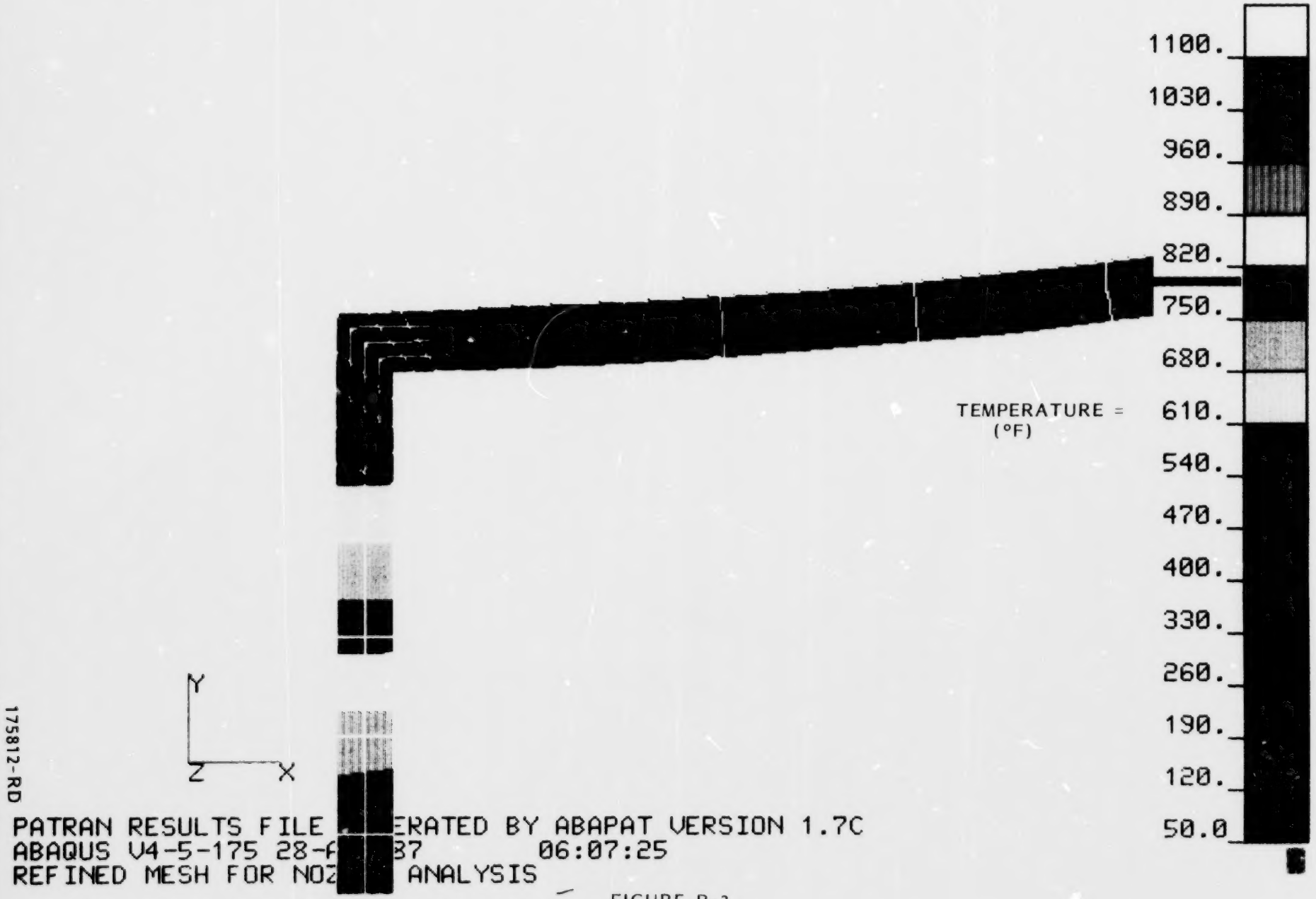

FIGURE B-2

TEMPERATURE DISTRIBUTION AT NOZZLE ROOT

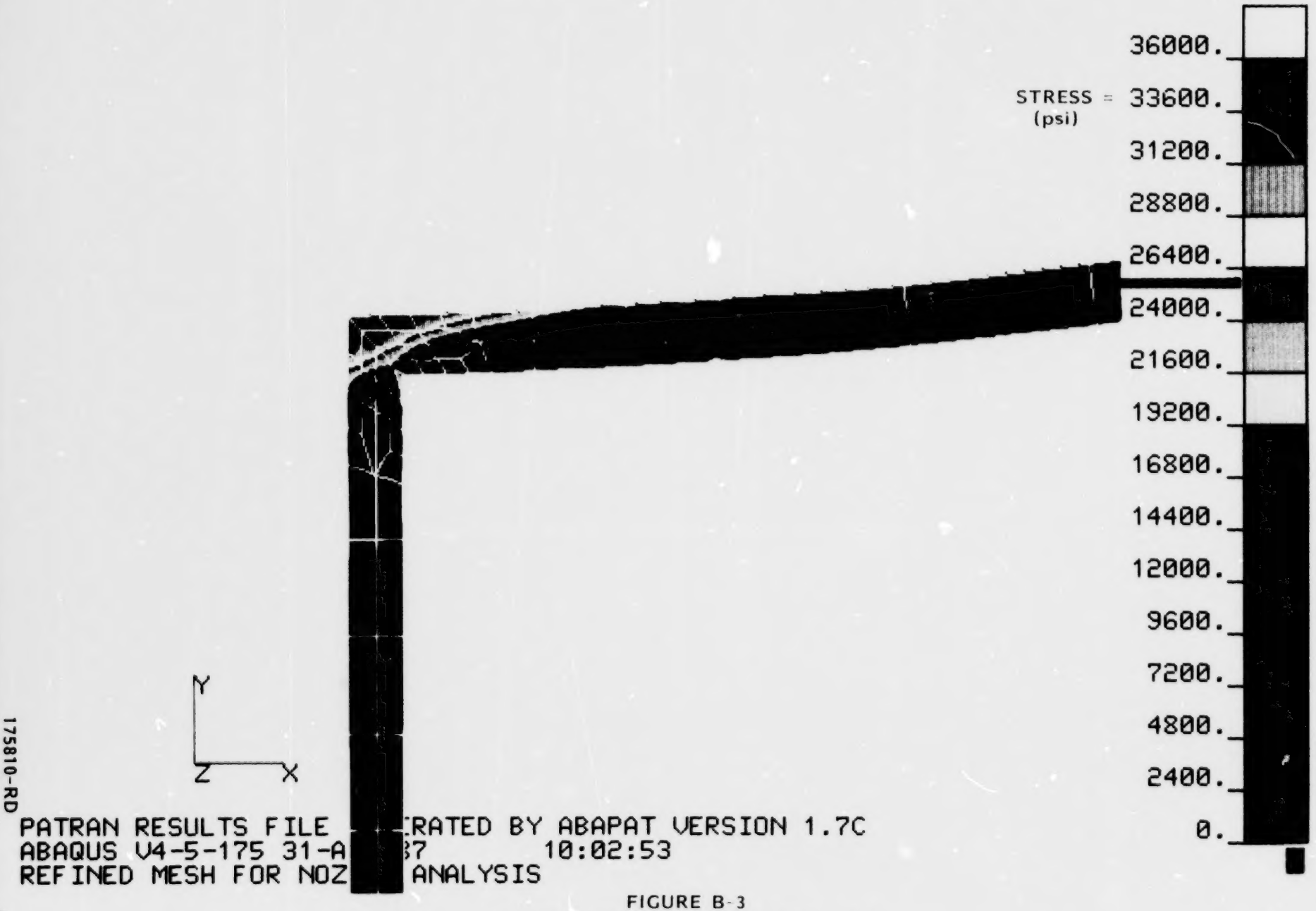

FIGURE B-3
MAXIMUM STRESSES AT NOZZLE ROOT

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FIGURE B-4
RESIDUAL STRESSES AT NOZZLE ROOT

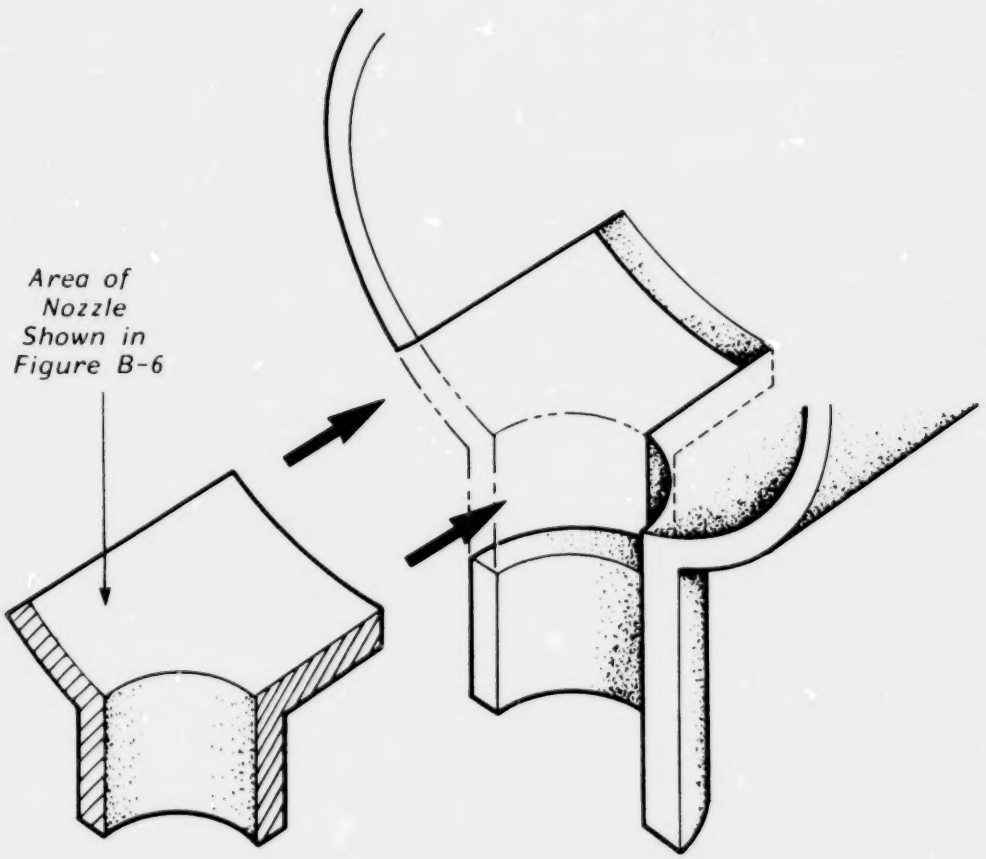

FIGURE B-5
SCHEMATIC VIEW OF SIX-INCH NOZZLE MODEL

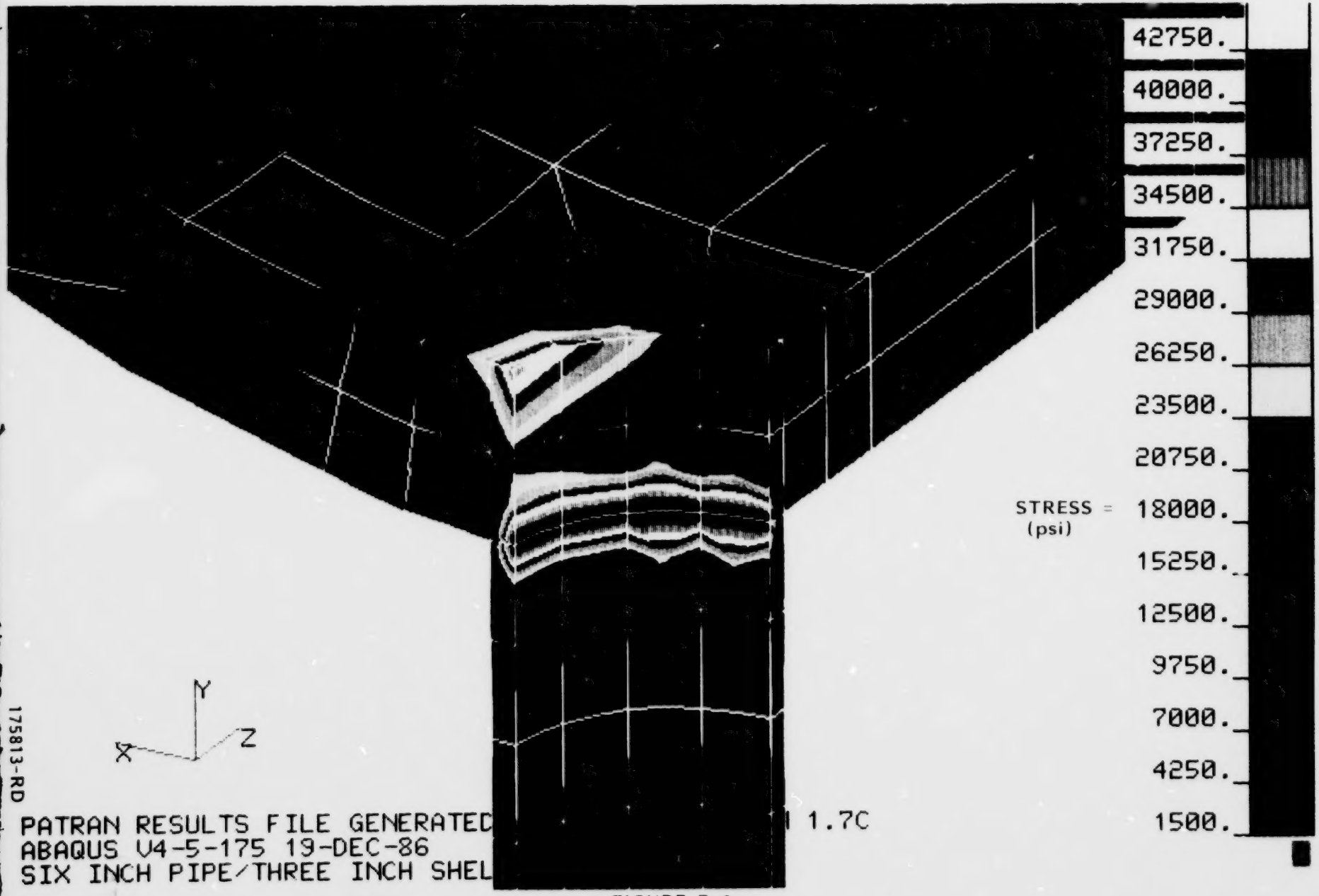

FIGURE B-6

PEAK STRESS CONTOURS IN SIX INCH NOZZLE

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